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Spacecraft Charging Effects

by

G. L. Wrenn

Procurement Executive, Ministry of Defence
Farnborough, Hampshire

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SUMMARY

This review describes how spacecraft surfaces become electrostatically charged in their interaction with incident space radiations, and discusses the consequential effects which can have dramatic impact on operations. An extensive chronicle of in-orbit 'anomalies' has now been gathered for geosynchronous satellites and it is possible to search for links between the timing and frequency of these 'events', flux measurements of charging particles, and solar terrestrial sources. This is a difficult exercise, due to the scarcity of suitable data, but results from European Space Agency METEOSAT and MARECS satellites are presented to define the boundary conditions of the problem. Special consideration of 'differential charging' and 'deep dielectric charging', with likely modes of breakdown, highlights the roles of energetic electrons, cold plasma concentration and secondary emission yields; while an outline of recommended prevention techniques stresses the merit of improved solar-geomagnetic predictions.

Invited paper presented at the Solar Terrestrial Predictions Workshop, Leura, Sydney, Australia, October 16 - 20, 1989

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SPACECRAFT CHARGING EFFECTS

Gordon L. Wrenn
Space Department, Royal Aerospace Establishment,
Farnborough, Hants GU14 6TD, U.K.

ABSTRACT

This review describes how spacecraft surfaces become electrostatically charged in their interaction with incident space radiations, and discusses the consequential effects which can have dramatic impact on operations. An extensive chronicle of in-orbit 'anomalies' has now been gathered for geosynchronous satellites and it is possible to search for links between the timing and frequency of these 'events', flux measurements of charging particles, and solar-terrestrial sources. This is a difficult exercise, due to the scarcity of suitable data, but results from European Space Agency METEOSAT and MARECS satellites are presented to define the boundary conditions of the problem. Special consideration of 'differential charging' and 'deep dielectric charging', with likely modes of breakdown, highlights the roles of energetic electrons, cold plasma concentration and secondary emission yields; while an outline of recommended prevention techniques stresses the merit of improved solar-geomagnetic predictions.

1. INTRODUCTION

The manufacture and launching of satellites is an expensive enterprise which is a 'high risk' business. It is therefore important that, once successfully injected into orbit, spacecraft continue to operate correctly until the end of their planned life. However, the space environment is hostile and experience shows that trouble-free operation will not be attained unless rigorous attention is paid to the potentially hazardous interactions of ambient particles/radiation with spacecraft materials and systems. There is now a large log of in-orbit malfunctions or 'anomalies' but it is usually impossible to positively identify their cause. One prime candidate for the source of many of these is electrostatic discharge (ESD), resulting from a local build up of charge to an extent that a breakdown threshold is exceeded. This process, termed spacecraft charging, occurs readily at exposed surfaces but also within dielectric materials close to an unshielded surface.

The geosynchronous orbit, which accommodates the majority of operational spacecraft, fosters extensive charging of surfaces due to the frequent absence of cold plasma, coupled with a flux of high energy plasmasheet electrons. In eclipse, it is possible for satellites to acquire floating potentials approaching -20 kV, but the real hazard arises from differential charging; this can easily occur with shadowed surface elements which are electrically isolated. At low altitude, the energetic electrons precipitate only in the auroral zones, but the concentration of plasmaspheric ions is usually such that it inhibits any build up of negative charge. However, there is now some concern that large polar platforms, traversing auroral latitudes during substorms, could be subject to serious differential charging, if sensitive surface elements are in shadow and wake. MeV electrons can penetrate and deposit charge within dielectric materials if the latter are unshielded (behind < 2 mm of aluminum) and such 'deep dielectric charging' is now considered to be a probable cause of many anomalies. The origin of these electrons is uncertain but their dynamics is subject to some solar cycle control.

Geomagnetic activity clearly controls both charging currents and anomaly occurrence; the search for causal links should reveal clues to the physical

processes involved, but what is an appropriate measure of geomagnetic activity ? Solar wind and IMF data or the derived dynamo power ε might be the best bet, but workers usually have to rely upon available indices such as K_p, a_p, A_p, A_k, AE or Dst; the perplexities of time-series analysis have then to be mastered.

2. OPERATIONAL PROBLEMS

Unmanned satellites are complex engineering systems which rely on internal emf supplies (usually solar powered), telecommand and telemetry radio links, and onboard computer control; they must function under conditions of high vacuum, zero gravity and variable thermal balance; requiring long life expectation without servicing. The overall record has been remarkably good, largely due to an appreciation of the need for thorough pre-launch testing and stringent quality control procedures. Given that all the flight systems die sooner or later and that failure analysis is often a matter of conjecture, the recognition of spacecraft charging related anomalies is far from easy. In recent years, many spacecraft managers have been all too ready to blame charging for operational hiccups. The problem is that few of the satellites experiencing anomalies carry instruments which can detect charging events, while the scientific satellites, equipped to study charging, have been carefully designed to be immune to ESD. Exceptionally, ATS (DeForest, 1972), METEOSAT (Wrenn & Johnstone 1987), DMSP (Gussenhoven et al., 1985) and SCATHA (Mullen et al., 1986, Li & Whipple, 1988) have produced important evidence for charging, but still failed to establish a conclusive pattern of cause and effect. However, there are many good correlations between the frequency and timing of anomalies and such variables as local time and geomagnetic activity indices which can classify charging levels.

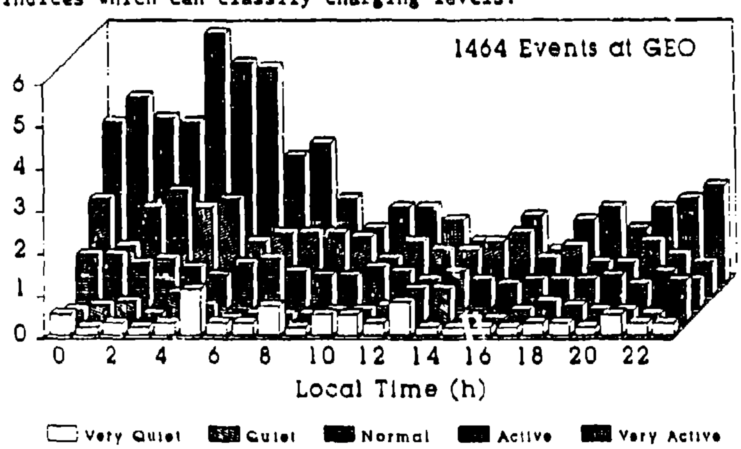

Fig 1. Diurnal distribution of spacecraft anomalies at GEO for five levels of geomagnetic activity; scale normalised to give a mean of 1. $a_p(0.9)$ thresholds are 5.6, 8.0, 20.5, and 29.7 (see Wrenn, 1987).

On 2 June 1973, DSCS-9431 suffered a catastrophic surge on its power system (Pike & Bunn, 1976); on 27 February 1982, MARECS-A switched from Earth pointing to Emergency Sun Re-acquisition mode (Capart & Dumesnil, 1983); on 26 November 1982, GOES-4 was fatally crippled (Allen & Wilkinson, 1986); on 8 March 1985, control of ANIK-D2 was lost when the antenna platform suddenly spun up (Wadham, 1987). These are some reported examples of serious anomalies which have been related to geomagnetic disturbances; undoubtedly, there have been many others. The National Geophysical Data Center at Boulder, Colorado, has assembled a Spacecraft Anomaly

data base (Allen & Wilkinson, 1986) with over 2000 entries; the number between midnight and 06 h is 64% above the average for the other 6 hour intervals, but Figure 1 shows that such an LT preference is largely limited to periods with very high geomagnetic activity. Most of the problems occur on satellites in geosynchronous orbit (GEO) where conditions are very often suitable for severe charging; detailed studies of the capricious environment and charging physics have been carried out on GEOS-2 and SCATHA. Commonly, anomalies produce phantom commands, logic upsets, spurious mode switchings and wrong status indications; rather than ESD, most are likely to be due to a telemetry glitch, mission control problem, part or system fatigue, thermal strain, radio frequency interference, electromagnetic pulse, or single event upset.

3. CHARGING MECHANISMS

The potentials of surfaces in space were excellently reviewed by Whipple (1981) and Garrett (1981). The equilibrium potential of a surface is established when the nett current to the surface is zero. The main sources of current (Fig 2) are:- charged particles from the environment - electrons and positive ions (mainly protons above 1000 km), back-scattered, secondary and photo- electrons emitted from the surface, and leakage to or from any underlying substrate.

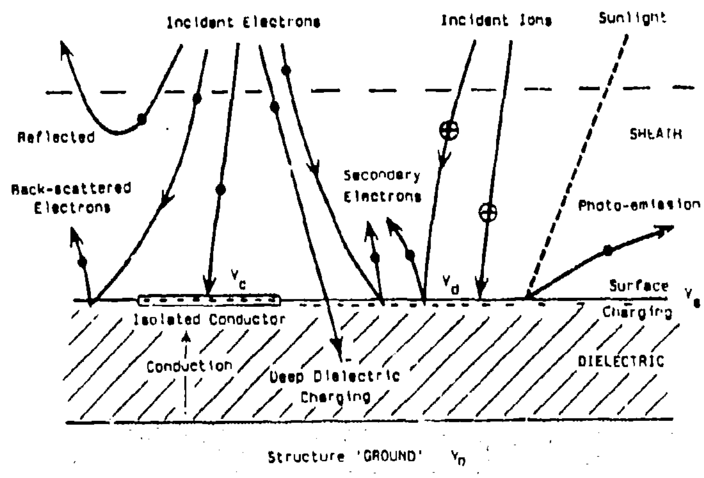

Fig 2. Currents which control charging at a spacecraft surface - isolated conductor or dielectric layer.

The potential difference between the surface and the substrate controls the latter component which is not always negligible, even for relatively good insulators. The surface currents are complex functions of their potentials; negative feedback limits the currents and tends to induce a dynamic equilibrium. A satellite structure ('ground') will float to an equilibrium potential, -19 kV was observed on ATS-6 (Olsen & Purvis, 1983), but such absolute charging represents no real hazard. Differential charging is much more dangerous. it can occur between surface elements and also within dielectric materials; consequent breakdown produces a discharge current transient, which can propagate through sensitive electronics systems on the spacecraft.

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3.1 ABSOLUTE CHARGING

In near-Earth orbit (LEO), within the plasmapause, potentials reach only a few volts negative or positive, depending upon the concentration of cold plasma and whether the surface is in shadow or sunlight. At higher altitudes, where $N_e < 10^2 cm^{-3}$, photoemission usually dominates the current balance but the effects of high energy particles become important. Plasmasheet fluxes, greatly enhanced in the midnight and early morning sectors at substorm injection, drive a spacecraft near GEO to large negative potentials. The flux of electrons, of a few keV to a few tens of keV, greatly exceeds that of any low energy ions that can be attracted. Figure 3 shows how mean charging currents vary with local time and geomagnetic activity, figure 4 illustrates how plasmasheet entry moves to earlier

Fig 3. Diurnal variation of charging current at GEO for three levels of geomagnetic activity: METEOSAT-2, Aug 81 - Mar 87.
Very Quiet, $K_p < 1-$
Normal, $1o < K_p < 3+$
Very Active, $K_p > 4+$

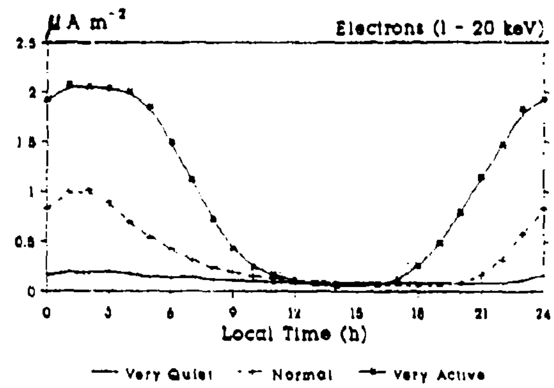
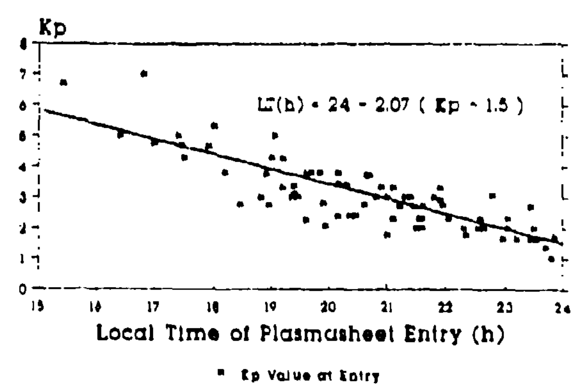


Fig 4. GEO plasmasheet entry times plotted against K_p: METEOSAT-2, 1981-5.



LT with increasing activity. In eclipse (< 75 min about local midnight in GEO), spacecraft potential can approach the -19 kV reported but in sunlight, it is limited to a few hundred volts (Mullen et al., 1986). In these situations the level of absolute charging is also dependent upon the secondary electron yield characteristics of the satellite surfaces (Katz et al., 1986). The rate of charging dV/dt, inversely proportional to capacitance ($\sim 4\pi\epsilon_0 R_s$), is typically several hundred volts per second.

3.2 DIFFERENTIAL CHARGING

Given that spacecraft surfaces are not all conducting and electrically connected, it is clear that large potential differences can develop between isolated surface elements, and between these and substrates or structure. Spacecraft ground still floats to minimise the net current and conducting surfaces are effectively tied to this. The level of charging depends upon the energy spectra of the incident particles, material properties, surface geometry and configuration as well as satellite orbit and attitude. Material properties play a vital role; conductivity and relative permittivity define the maximum rate of charging but the yield coefficients for photo- and secondary electron emission control critical components of the nett charging current. Since the capacitances associated with differential charging can be high, the charge times are relatively long (many min) and temporal constraints, e.g. satellite spin, are important. Sunlight with shadowing probably introduces the greatest contrast but other asymmetries rise from satellite motion (ram and wake perturbations), the geomagnetic field (the energetic electron fluxes are field-aligned) and the $\underline{v} \times \underline{B}$ induced electric fields. The process is complicated by the fact that surfaces are coupled via the plasma, space charge sheaths develop and the local electric field is complex; secondary emitted electrons from one surface can be attracted to another and potential barriers can reflect incident or emitted fluxes (Purvis, 1983). Even small concentrations of plasmaspheric ions will quickly neutralize any significant charging. A GEO satellite usually encounters the plasmasphere in the dusk sector, while in quiet times the whole orbit can be inside this region of cold plasma. Figure 5 shows how mean concentration varies with LT and geomagnetic activity.

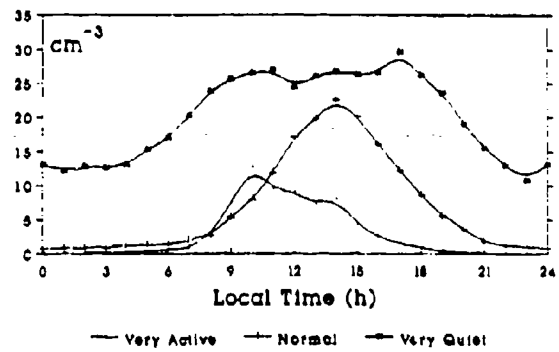


Fig 5. Diurnal variation of mean cold plasma concentration at GEO for 3 levels of geomagnetic activity: GEOS-2, 1978-80.

There is no doubt that differential charging is responsible for many ESD problems on GEO missions. Lechte (1987) reported that 90% of MARECS-A anomalies were between 00.30 and 06.30 LT, see figure 6; they were usually at geomagnetically active times (Capart & Dumesnil, 1983).

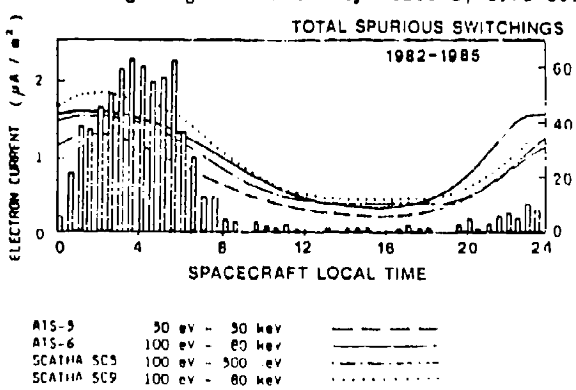


Fig 6. Diurnal spread of MARECS-A spurious switchings compared with average profiles of measured currents.

Since the energetic electrons are regularly precipitated to low altitudes in the auroral zones, the ingredients exist for similar problems to occur at LEO for high inclination orbits. Significant charging has been observed (Gussenhoven et al., 1985) but there is no history of related anomalies; the larger dimensions of proposed polar spacecraft will increase susceptibity (Katz & Parks, 1983).

3.3 DEEP DIELECTRIC CHARGING

More energetic electrons, hundreds of keV to several Mev, can penetrate to considerable depth in a dielectric and deposit charge within the bulk material. If the rate of deposition exceeds the rate at which charge leaks away due to the intrinsic conductivity, potential differences can reach the threshold for breakdown, resulting in a discharge (Vampola, 1987). Such fluxes of electrons do appear in the outer magnetosphere; their diurnal distribution is different to that of keV electrons, peaking around noon, and many day-side anomalies are attributed to this mechanism (Baker et al., 1987). The GOES-5 mission was greatly compromised by a filament failure during a 12 day 'event' in July 1984 when 3-5 MeV electron intensities increased by ~ 3 orders of magnitude. It is envisaged that this type of charging is slow, taking hours or days; total fluence (integrated flux) becomes the critical parameter. Unshielded components close to a spacecraft surface e.g. cables, present the principal problem; 2 mm of aluminium or equivalent will stop most of the offending electrons i.e. those below 1 MeV. Figure 7 shows how mean flux reduces with energy (Baker et al., 1981) while range decreases (Seltzer, 1979).

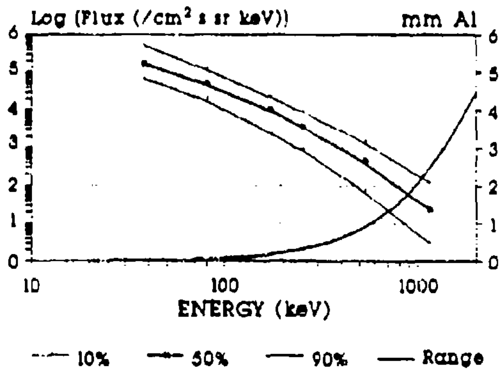


Fig 7. Mean fluxes of energetic electrons at GEO and their range in Aluminium.

4. MODES OF BREAKDOWN

Breakdown can be induced across surfaces, through substrates or to space (blow-off); isolated charged surfaces, either dielectric or conducting, will lose charge slowly by conduction to the substrate. They will discharge quickly to space if they become sunlit or encounter higher concentrations of cold ions, (plasma clouds are not uncommon at GEO) but such transients are not directly conducted to the rest of the spacecraft; neither are those due to arcing between isolated surfaces, although radiated interference might be generated. Output from an earth sensor aboard ANIK-A gives a neat demonstration of periodic discharging of a metal lens barrel by photoemission (Wadham, 1987). Discharges involving a conductor electrically connected to the structure are likely to be more damaging because large current spikes (many amperes) can be conducted or inductively coupled into any sensitive circuit. Floating conductors (e.g. metallized coating of thermal blankets) break down more readily than dielectrics, but the latter can support a greater buildup and the discharge, propagating from a source point, will still sweep across the entire surface. Discharge produces strong electric field and space charge modification around the satellite and a sudden drop in absolute potential, these can cause additional indirect effects. Breakdown is an event lasting not more than a few hundred nanoseconds but a burst or cascade of such events might occupy several tens of microseconds. If the many anomalies occurring at geomagnetically quiet times or on the day-side, remote from the enhanced electron fluxes, are due to ESD then there seem to be only two explanations. Either they are caused by energetic electrons or there is a long delay, up to many hours, between charge and a triggered discharge.

5. LINKING ANOMALIES TO CHARGING

Proof that many anomalies are due to differential charging of sensitive surface elements is based upon the common diurnal patterns of anomalies and charging fluxes, and the absence of anomalies during eclipse (e.g. MARECS-A). However, it is the common dependence upon geomagnetic activity which makes such evidence conclusive. A direct link between time of ESD and integrated charging current has yet to be demonstrated.

Other anomalies occur at all local times and during geomagnetically quiet periods, their explanation is still a puzzle. Figure 8 shows that METEOSAT anomalies are spread fairly evenly in LT. Charging, surface or deep dielectric, probably plays a role but the search for clues urges more correlated measurements of both MeV electrons and cold plasma; defining the solar-geomagnetic control of either is therefore crucial. Initial results from METEOSAT-3 indicate that these anomalies do tend to coincide with enhanced fluxes of 43 - 300 keV electrons and high A_p.

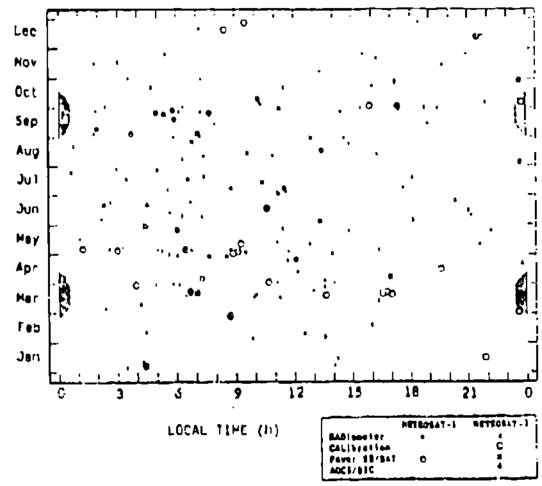


Fig 8. Distribution of METEOSAT anomalies in local time and season of year: METEOSAT-1, 1977-9; METEOSAT-2, 1981-5.

6. GUIDELINES FOR PROTECTION

The prevention of ESD due to surface charging is simple - eliminate all exposed dielectrics and isolated conductors; unfortunately this tends to be either impossible or prohibitively expensive. Deep dielectric charging will be effectively suppressed by shielding (~1.5 mm of aluminium) but it is not feasible to stop electrons with very high energy (several MeV). 'Design guidelines for assessing and controlling spacecraft charging effects' have been issued by NASA (Purvis et al., 1984), these should be adopted wherever possible.

6.1 LIMITATION OF CHARGE BUILD-UP

Adequate grounding ($<1M\Omega m^2$) of surface conductors is usually not a difficult exercise and is strongly recommended. This includes all structural or mechanical strength components, metallic coatings of plastic films used for thermal control, cable screens, printed circuit trays, etc. The use of excessively insulating materials, e.g. fluoropolymers such as teflon, epoxy-fibreglass composites and mylar, should be avoided. Now available are 'leakage' dielectric materials such as are carbon-filled teflon and thin-layer kapton polyimides, and also conducting paints. Indium tin oxide (ITO) coatings are transparent and have been used successfully where thermo-optical properties must be retained, e.g. large area solar arrays, second surface mirrors, and kapton blankets; tests have been carried out with ion implantation of kapton and solar cell cover glasses (Verdin & Duck, 1987).

6.2 CIRCUIT PROTECTION

Designers of satellite electronics have always had to meet high standards in respect of electromagnetic interference suppression, and rules of good practice have evolved. Since the susceptibility of components continues to increase, there is no room for complacency and new devices must be rigorously tested. Cable forms and grounding schemes must be considered critically; it is often possible to introduce filters for the fast discharge transients. In some cases, actuators or memories have unnecessarily high speeds and these can be desensitized by adding delay components (Lechte, 1987) without degrading the response. Circumvention may be sometimes be feasible (it was attempted on MARECS-A) when susceptible circuits are disabled on a substorm alert; unfortunately, prediction services are really less than adequate for such a procedure to be efficient.

6.3 MODELLING AND QUALIFICATION

A better understanding of spacecraft charging has been achieved with the help of computer modelling programs. NASCAP (Katz et al., 1983) is a 3D code which permits a dynamic simulation of the electrostatic charging processes; it is a valuable tool for assessing the likelihood of problems and quantitatively evaluating possible solutions. Similar codes for LEO and POLAR applications are being developed. It is not normally practicable to place a spacecraft in a vacuum chamber and study the effects of electron irradiation but special tests at subsystem level might be contemplated. Alternatively, simulated signatures of discharges can be injected during the programme of qualification, and testing on the integrated spacecraft.

6.4 IN-FLIGHT MONITORING

There is still a need for data specific to operational satellites which exhibit peculiar charging characteristics; it would be very desirable if each could carry some suitable monitors, such as electron or ion spectrometers, surface potential probes and transient analyzers. A simple Langmuir probe, with fixed negative bias to detect thermal ions, would be particularly valuable. Small instruments with minimal mission constraint could solve the outstanding questions far more reliably than any simulations which may be carried out on the ground.

7. CONCLUSIONS

Experience suggests that even if all the recommended procedures are followed, geosynchronous spacecraft will continue to suffer malfunctions as a consequence of charging. The greatest threat arrives at intervals near maxima of the solar cycle (1989 and 1990 promise to be very active). To avoid serious problems, it is probably best to design for discharges to be frequent and small, rather than rare and large. It is fortunate that almost all malfunctions are overcome by controller action but not without some cost in terms of loss of data, reliability and mission life; increased staffing and vigilance also have a price.

There is still no complete explanation for numerous day-side anomalies. It appears that energetic electron fluxes are seldom high enough to yield the fluences necessary to cause discharges in thick dielectrics. On the other hand, it is rare that cold plasmaspheric ions are totally absent around the orbit, and thus surface elements seem unlikely to remain highly charged for many hours; if they do, then one is faced with the question of what the discharge trigger mechanism could be.

Recently there has been much interest in proposals for large polar platforms in LEO and possible charging hazards have been identified; the coincidence of wake, shadow and substorm could be ominous, see figure 9.

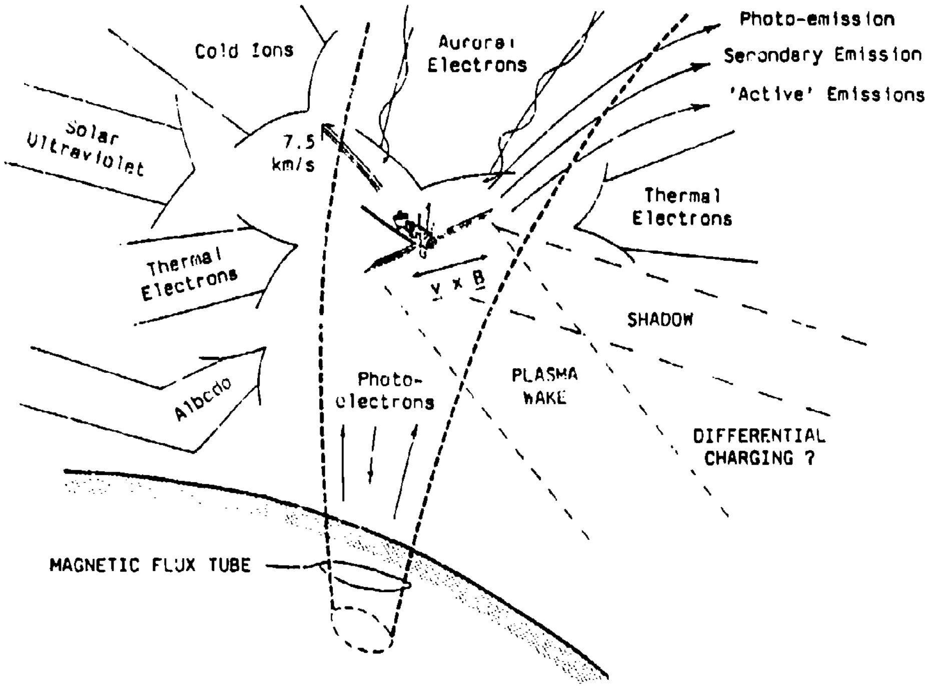


Fig 9. The charging environment for a polar platform in low Earth orbit.

Astronaut EVA's above auroral arcs are certainly to be discouraged for the time being. Innovative systems such as high voltage solar arrays, tethers, ion thrusters, plasma contactors and particle beam emitters, introduce new challenges for the charging analyst.

Dangerous spacecraft charging effects can be eliminated, but at a cost. The requirement for long-life missions is dictated by economics, as is the level of protection to be afforded. The right compromises cannot be made without solving the outstanding questions, many of which reflect an inadequate knowledge of the solar terrestrial environment.

8. ACKNOWLEDGEMENTS

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17. Abstract

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